The first billion years of the geodynamo

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Paleomagnetic data from single silicate crystals hosting magnetic inclusions, and rocks whose magnetization is dominated by single silicates with magnetic inclusions, provide a consistent picture of a strong geomagnetic field, within 50% of the present day field strength, during Archean to Paleoarchean times (3.45 Ga) without sign of interruption (although large time intervals remain unsampled). Paleomagnetic investigation of Eoarchean to Hadean zircons, bearing magnetic inclusions from the Jack Hills (JH) of Western Australia, suggest the presence of an even older geodynamo, as old as 4.2 Ga. The natural remanent magnetizations of these these zircons are reproducible, when measured with an ultrasensitive small bore SQUID magnetometer and a scanning SQUID microscope. New Li data suggest that Hadean zircons studied by Tarduno et al. (2015) have not been reheated above ~500 ˚C since their formation, supporting prior conclusions based on SHRIMP analyses that these zircons preserve a primary remanence. Novel techniques developed by our group provide evidence for multiple magnetic source regions within these zircons. New paleomagnetic data from an Eoarchean to Hadean-bearing zircon locality of the Southern Cross Terrane of Western Australia, >400 kilometers from the Jack Hills, pass a microconglomerate test, yield preliminary paleointensities of ~4-27 microTesla, and thus further support the presence of a very ancient geodynamo. Here we will review the Archean to Hadean geomagnetic record, our recent tests of its fidelity, and its implications for the early evolution of the core and atmosphere.

Keywords: Geodynamo, Hadean, Zircons, Core, Paleointensity, Magnetic shielding

Paleomagnetic studies on single crystals separated from the middle Cretaceous Iritono granite

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To study the evolution of the geomagnetic field and its relationship to the thermal evolution of the Earth and mantle convection, the long-term behavior of the geomagnetic field should be emphasized. Granitic rocks could be good candidates to investigate the long-term evolution of the geomagnetic paleointensity because their long cooling times can average out relatively short-term fluctuations of the geomagnetic field. However, paleomagnetic measurements of granitic rocks are often disturbed by alteration like weathering and lightning, and the effects of multi-domain state magnetite. Recently, several research groups have investigated paleointensities from single crystals of primary minerals such as plagioclase, pyroxene, zircon and quartz for their potential to avoid difficulties that frequently plague whole-rock measurements (e.g. Tarduno et al., 2007; Usui et al., 2015; Sato et al., 2015). To provide solid ground for single silicate crystal paleomagnetism, paleointensity and rock-magnetic properties of single crystals should be systematically studied and compared to those of the host granitic rock.
We separated zircons, quartz and plagioclases from a Cretaceous granite sample whose whole-rock paleointensity and rock-magnetic properties were studied previously, and found to be particularly stable and reproducible (100 Ma, Wakabayashi et al., 2006; Tsunakawa et al., 2009). Superconducting quantum interference device (SQUID) magnetometer and magnetic property measurement system (MPMS) were used to measure natural remanent magnetization (NRM), isothermal remanent magnetization (IRM), thermal remanent magnetization (TRM), anhysteretic remanent magnetization (ARM) and low temperature magnetic properties of the single crystals.
Zircons with grain size of >100 μm were selected for measurements. Less than 1% of them had NRM intensity larger than 10 pAm^2. Low temperature magnetic properties and stepwise thermal demagnetization suggested that the major magnetic carrier of these zircons were pyrrhotite, and thus, the zircons are inappropriate for the paleointensity study. Quartz showed similar NRM intensity distribution with zircons. However, some quartz grains showed similar blocking temperature profiles with the host-rock, and primary magnetization components were detected on the orthogonal projections, indicating that these quartz could be suitable for paleointensity study. 44% of plagioclases had NRM intensity greater than 10 pAm^2. Their NRM/IRM ratio and low-temperature magnetic properties suggested the existence of tiny magnetite inclusions possibly exsolved from plagioclase. We performed paleointensity measurements by the Tsunakawa-Shaw method (Yamamoto et al., 2003) to four plagioclase crystals. The obtained paleointensities (46-77 μT) were consistent with the reported whole-rock paleointensity.

Keywords: paleointensity, granite, single crystals

Depth variations of paleointensities in lava flows from Izu-Oshima revisited

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Reliable paleointensity data from lava flows are still difficult to be obtained compared to those from archeological materials. Since Nagata, Arai and Momose [1963] deduced paleointensities from basalt lava flows in Izu-Ohshima volcanic island for the past 1000 years, the paleointensity data have been accepted as representing the vector secular variation of the geomagnetic field in Japan [Yoshihara et al., 2003]. Although the directional secular variation from Izu-Oshima is concordant with archeomagnetic data and historical geomagnetic model gufm1, the paleointensities of Nagata et al. [1963] and Yoshihara et al. [2003] gave discordant values to each other even for same lava flows by several tens of percent and to those from archeological materials.

I collected paleomagnetic drill cores or hand samples from vertical sections of several lava flows erupted during the past 700 years. At some sites I could find drill holes of Nagata et al. [1963] and Yoshihara et al. [2003] and retrieved drill cores next to the holes. The lava flows were relatively thin (usually lava thickness < 1 m) and the entire sections can be recovered. Especially I focused on upper and lower clinkers for sampling even if orienting device was not possible to use.

Thellier paleointensity measurements were performed using a fully automated magnetometer-furnace system tspin for about 150 specimens. I chose appropriate temperature steps for each specimen based on the thermomagnetic curve that was quite variable depending on the vertical position within a lava flow. Grain size inferred from hysteresis parameters also systematically changed according to the vertical position: smaller grain size in upper and lower clinkers and larger grain size in lava’s interior.

I could not find linear segments on Arai diagrams for most of the measured specimens; Upward concave, two-segment or sigmoid curves are common. Exceptionally linear segments were observed for a small number of upper or lower clinker samples that have very high Mr/Ms (~0.5) indicating single domain grains. However, any samples from lava’s interior of the same vertical sections did not show linear segments. Sometimes slightly upward concave curves seem to be straight, giving erroneously high paleointensities.

Drill cores collected near remnant drill holes of Nagata et al. [1963] and Yoshihara et al. [2003] did not provide any paleointensity data. These cores come from lava’s interior and no linear segment was identified on Arai diagrams. Therefore the existing intensity secular variation from Izu-Oshima lava flows must be taken with great caution. This finding also suggests that Thellier paleointensity data from lava interiors need to be reexamined.

Keywords: paleointensity, geomagnetic secular variation, hysteresis properties, Curie temperature

Further archeointensity study on potteries fired in the reconstructed ancient kiln in Japan

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Yamamoto et al. (2015) reported that baked clay samples from the floor of a reconstructed ancient kiln provided a reliable archeointensity estimate of 47.3 +/- 2.2 microT which is fairly consistent with the in situ geomagnetic field of 46.4 microT at the time of the reconstruction. The reconstruction was conducted to reproduce an excavated kiln of the seventh century in Japan and potteries of contemporary style (Sue ware) were also fired (Nakajima et al., 1974). We have been performing archeointensity determinations on the potteries using the Tsunakawa-Shaw (LTD-DHT Shaw) method.

We cut mini specimens from a cup type (CupB-1) and a sake-pitcher type (Tokkuri-1) potteries. For the CupB-1 all the specimens were heated in vacuum for acquisition of laboratory thermoremanent magnetization (TRM), and 15 out of the 17 specimens passed the criteria to yield an archeointensity estimate of 65.8 +/- 2.5 microT. This is significantly higher than the in situ geomagnetic field of 46.4 microT (about 40 per cent high). Anisotropy of remanent magnetization is not seemed to be a possible cause of the high archeointensity estimate because it is only 3 per cent between the natural remanent magnetization (NRM) directions and laboratory TRM directions based on measurements of anhysteretic remanent magnetization (ARM). We reported these preliminary results from the CupB-1 in last November (Yamamoto et al., 2016 SGEPSS meeting).

Other possible cause of the high archeointensity estimate is uncorrectable laboratory alteration using ARMs. It is expected that different type of alterations could occur between heating in vacuum and air. For the Tokkuri-1 the specimens were split into two groups: one was heated in vacuum while the other was in air. So far we have obtained 6 successful results: 67.1 +/- 12.5 microT for the vacuum group (N=2) and 49.1 +/- 2.6 microT for the air group (N=2). We will continue the experiment and discuss these results.

Pseudo single domain magnetite as a stable natural remanent magnetization carrier in obsidian

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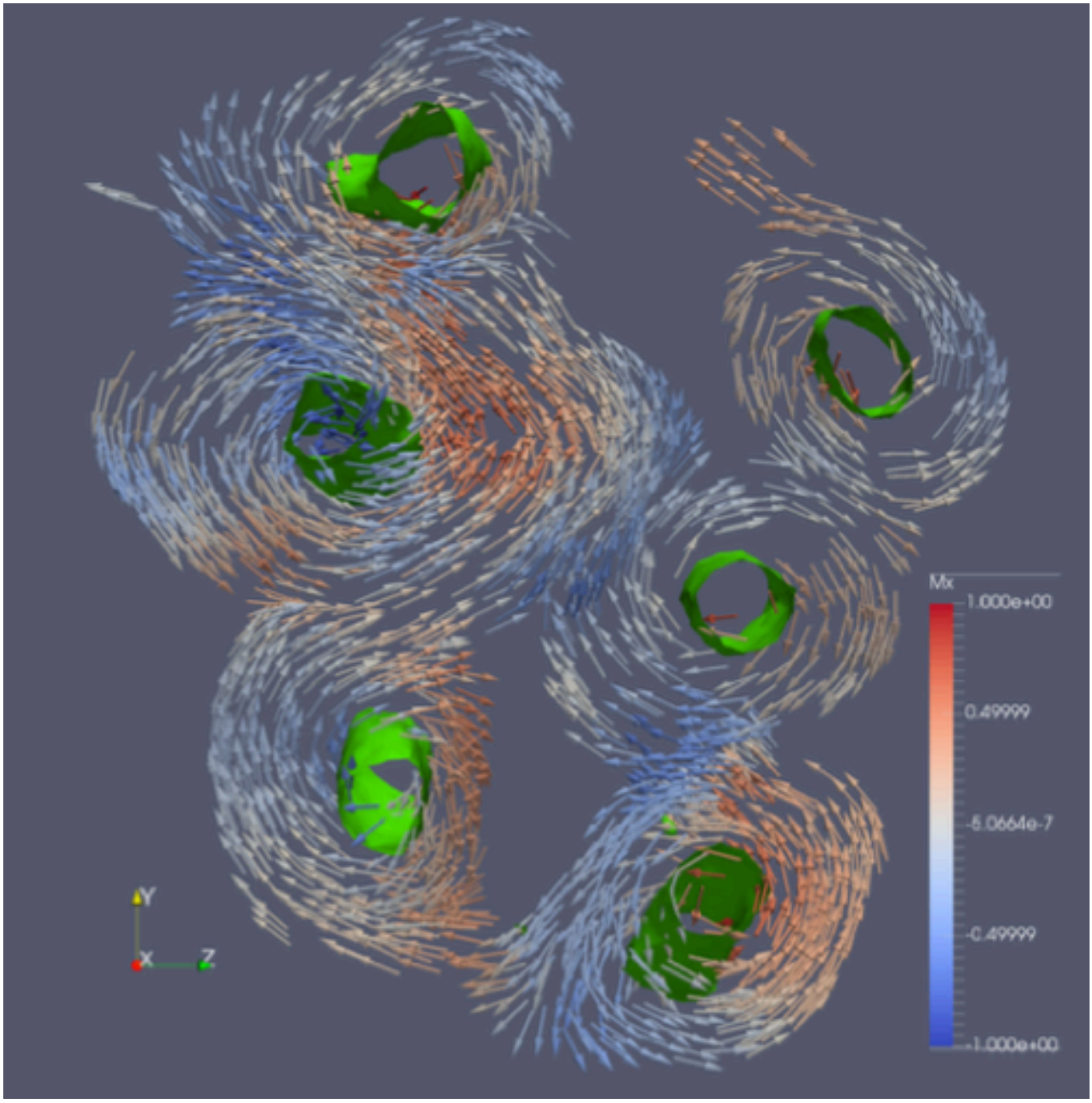
Most natural samples contain so-called “non-ideal” paleomagnetic recorders, which are magnetic particles larger than ideal, single domain recorders, but smaller than proper multi domain grains, which are poor paleomagnetic recorders. The grain size range for these recorders, which for magnetite comprises grains from ~100 nm to a few μm in size, is known as the pseudo single domain (PSD) domain state. Natural samples containing abundant PSD grains have been shown to reliably record thermomagnetic remanent magnetizations that are stable over billions of years. Here we investigate obsidian varieties from Glass Butte, Oregon, USA, which present the opportunity to study the simple case of PSD grains encapsulated in volcanic glass. To do this, we combine paleointensity experiments, rock magnetism, scanning electron microscopy (SEM) nanotomography, and finite-element micromagnetic modelling. Results from the Thellier-IZZI protocol indicate that PSD grains acquire a thermoremanent magnetization efficiently and have high blocking temperatures, similar to stable single domain grains. Using rock magnetism we identify PSD signatures via their diagnostic fingerprint in first-order reversal curve (FORC) diagrams. Tomographic reconstructions obtained by stacking SEM images acquired via sequential milling through sample volumes of a few tens of cubic μm reveal the presence of abundant grains that span the PSD grain size interval. These grains have a variety of shapes, from simple ellipsoidal particles, to more complex morphologies attained via the coalescence of neighbouring grains during crystallization, to intricate “rolling snowball” morphologies that formed during growth in a dynamic environment as the flowing lava cooled. Micromagnetic modelling of the simplest morphologies reveals that these grains are in single vortex states, with the remanence controlled by irregularities in grain morphology. Larger grains contain complex, multi-vortex structures and incipient domain walls, with remanence being controlled by the collection of PSD states from areas with pronounced shape anisotropy. Modelling the properties of these grains as a function of field and temperature allows a better understanding of PSD remanence acquisition in natural samples.



Environmental Magnetism of Cave Deposits

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Caves are deep time archives of environmental conditions at the surface. Traditional paleoclimate proxies, such as oxygen and carbon isotopic ratios, are preserved within actively growing carbonate speleothems and can be constrained in time using high-resolution 230Th geochronology. While these isotopic speleothem proxies have revolutionized paleoclimate studies, here we discuss the use of magnetic measurements to constrain changes in the flux of Fe-bearing minerals (their composition, concentration, and magnetic grain size distribution) within the context of environmental change.

Fe-bearing minerals can occur within speleothems due to a variety of transportation and nucleation & growth mechanisms. Drip waters carry trace concentrations of Fe-bearing minerals from overlying soils and dissolved and eroded bedrock. Flood waters that temporarily fill a cave passage will leave behind thin films of silt- and clay-sized sediment, some of which contain Fe-bearing minerals. Some minerals, such as goethite, are thought to nucleate and grow in pore spaces in the overlying rock and to be deposited via dripwater onto actively growing stalagmites. Alternatively, changes in the Eh and pH conditions of groundwater as it equilibrates with the open air environment of a cave may cause dissolved Fe to nucleate and grow goethite directly on the surface of carbonate speleothems. Thus, while the incorporation of Fe-bearing minerals into speleothems is primarily a function of surface environmental conditions, including precipitation patterns, mean annual temperature, and pedogenic productivity, secondary processes within a cave environment can also contribute to Fe-minerals in speleothems.

Here we present some promising examples of how the magnetic properties of Fe-bearing minerals preserved within speleothems can provide environmental information on short (e.g., decadal) and long (e.g., millennial) timescales that is independent and complementary to existing paleo-environmental proxies.

Keywords: Caves, Speleothem, Paleoclimate, Soil, Environmental magnetism, Magnetic properties

Paleomagnetic secular variation and environmental magnetic records for the last 600 years from Lake Petexbatun sediments in Maya lowlands

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Laguna Petexbatun is located in Maya lowlands where the Mesoamerican civilization developed prior to the 16 Century. As a part of the research project titled “Comparative Studies on Ancient American Civilizations,” several core samples were recovered for paleoenvironmental analysis mainly from a depression of about 40 m deep in the lake bottom. The sediments in the depression consist of grey mud with relatively thick annual varves, which are utilized for core-to-core correlation and construction of a composite depth scale of about 7.5 m long. AMS radiocarbon dates of fossil leaf fragments and varve counting indicate that the composite section covers the time period for the last 600 years. We made magnetic measurement of LL-channel samples from two long piston cores and additional short cores containing surficial sediments in order to investigate paleomagnetic secular variation (PSV) records and variations of magnetic properties reflecting environmental changes. Characteristic components of remanent magnetization obtained through principal component analysis of stepwise AF demagnetization show gradual increase of inclination values from about A.D. 1600 to the present. This variation is concordant with the global PSV models such as gufm1 and pfm9k.1a, and with the IGRF12 in the topmost part. Magnetic concentration parameters, including low-field magnetic susceptibility, anhysteretic magnetization, isothermal remanent magnetization (IRM) at 1 T, and high coercivity (0.3-1.0 T) component of IRM (HIRM), show consistent variation among the cores, suggesting decadal to centennial changes of magnetic mineral flux into the lake bottom. Particularly, the variations of IRM at 1T and HIRM can be well correlated to the yearly mean and monthly smoothed sunspot number record since A.D. 1700 characterized by 11-year and 88-year cycles. Thus magnetic properties of the Lake Petexbatun sediments provide geological evidence that the Mesoamerican climate has been modulated by the solar activity.

Keywords: magnetic properties, varve, sunspot

A relative paleointensity record of the last 3.2 m.y. from western equatorial Pacific and remanent magnetization lock-in depth

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We conducted a paleomagnetic study on a sediment core (MR14-02 PC01) taken from the western equatorial Pacific. The aim of this study was firstly to obtain a relative paleointensity (RPI) record older than 2 Ma; the number of available RPI records older than 2 Ma was still limited, and a global stacked curve has not yet been established. Another aim was to examine the controversial lock-in depth of remanent magnetization acquisition by comparing RPI and ^{10}Be abundance profiles during polarity transitions.

Core PC01 covers the last ~3.2 m.y. with an average sedimentation rate of 5 m/m.y. Magnetic properties of the sediments satisfy the criteria for reliable RPI estimations, and a RPI record from ~0.6 to ~3.2 Ma was obtained by normalizing NRM intensities with SIRM. A reliable age model based on the oxygen-isotope (δ^{18}O) stratigraphy was established for sediments older than 1.8 Ma. The RPI record up to 2 Ma from core PC01 agrees in general with the paleointensity stacks PISO-1500 and Sint-2000. However, long-term trends of the RPI record show anti-correlation with the ratio of ARM to SIRM, as pointed out for other cores by Yamazaki et al. (2013). This suggests that changes in the ratio of biogenic to terrigenous magnetic mineral component in the sediments may have contaminated the RPI record.

RPI and ^{10}Be flux of core PC01 did not show any obvious offset around the onset of the Olduvai subchron and the Gauss-Matuyama transition. This implies a negligibly small lock-in depth for core PC01. We also examined the lock-in depth of core PC01 by comparing δ^{18}O based ages of recorded polarity boundaries and GPTS ages, and by comparisons of RPI records among PC01, nearby MD982187 core (Yamazaki and Oda, 2005), and IODP Site U1314 in the North Atlantic (Ohno et al., 2012), which have different sedimentation rates. The results were consistent with the negligibly small lock-in depth of core PC01. A lock-in depth of ~0 cm was also reported from Indian Ocean sediments by Valet et al. (2014). It was revealed that lock-in depths obtained from sediment cores in the same region by the identical method are different: ~15 cm for MD982187 core (Suganuma et al., 2010; 2011), ~6 cm and ~10 cm for two cores of Horiuchi et al. (2016), and ~0 cm in this study. Lock-in depth may be controlled by small differences in lithology and depositional processes of individual cores through mechanisms that we do not yet understand.

Keywords: paleointensity, Beryllium isotope, DRM lock-in depth

Paleomagnetic and paleoclimatic records through the Matuyama-Brunhes boundary from the Chiba composite section, southeastern Japan

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The Marine Isotope Stage (MIS) 19 is thought to be an important analogue for evaluating the climate system of the present interglacial (MIS 1), because of the similarity of the Earth’s orbital configuration, especially the phasing of obliquity maximum to precession minimum. During the MIS 19, the youngest geomagnetic polarity reversal, the Matuyama-Brunhes (M-B) boundary, has been recongnized at the later part of the interglacial period in marine/lake sediments and Antarctic ice core (e.g., Dreyfus et al., 2008; Channell et al., 2010; Simon et al., 2017). Recently, the influence of geomagnetic field intensity to the climate was reported based on anomalous cooling events observed during the M-B boundary and the other reversal from pollen records from Osaka Bay (e.g., Kitaba et al., 2013; 2017). During the M-B boundary, the cooling event, coincides with the middle part of the paleomagnetic intensity low, just before the sea-level highstand correlated with the MIS 19c, followed by a rapid warming and concurrent paleointensity recovery. In order to address this topic, we carried out a very detailed pollen analysis from the most expanded marine sedimentary record throught the MIS 19 in the Choba composite section, southeastern part of Japan. A newly obtained high-resolution oxygen isotope stratigraphy provides robust time control for the studied section. In this record, however, no significant palynological changes were observed across the horizon of the M–B transition interval. This indicates that a climatic change related with the geomagnetic field reversal was not obvious in the southeastern part of Japan.

A paleomagnetic record across the Mammoth reversed subchron reconstructed from the upper Pliocene Anno Formation, Awa Group, central Japan

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The Awa Group, distributed in the central Boso Peninsula, central Japan, is a suit of marine succession for contiguous paleomagnetic studies, because of its strong magnetization and abundant marine microfossils used for age constraints. In this study, we obtained a successive paleomagnetic record across the Mammoth reversed subchron from the upper Pliocene Anno Formation, Awa Group.
Rock samples for paleomagnetic and foraminiferal oxygen isotopic analyses were collected from the Shikoma River, Terao and Nagasaki sections in Futtsu city, Chiba. Mini cores with 1-inch diameter and hand-picked specimens with about 300 g by dry-weight were collected at 80 horizons at every 0.5-1.0 m stratigraphic interval.
We performed progressive alternating field demagnetization (pAFD), progressive thermal demagnetization (pThD) and various rockmagnetic analyses to extract primary components from the specimens and verify the stability of the remanence. The results for rockmagnetic analyses exhibit the most specimens have pseudo-single domain magnetites as the magnetic carrier of natural remanent magnetizations. We carried out the reversal tests, one of the field tests, and the data from both demagnetization methods are passed. Therefore, we calculated the Virtual Geomagnetic Polarity (VGP) by using the ChRMs from pThD, which exhibt a better result in the reversal test than pAFD.
The VGP path during ca. 3.35–3.19 Ma, including the Mammoth reversed subchron, was reconstructed. The VGPs across the upper and lower Mammoth boundaries are through the northeastern Africa and the southern Pacific off Chile, respectively. These VGP paths across the upper and lower Mammoth boundaries are similar to those from a sedimentary section in Sicily (Linssen, 1991) and from the Wai’anae volcano in Oahu (Herrero-Bervera et al., 1999; Herrero-Bervera and Valet, 2005).

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Keywords: Mammoth reversed subchron, Virtual Geomagnetic Polarity, Oxygen isotopic stratigraphy, Paleomagnetism

The strongest crustal magnetic field generated by back-arc basaltic volcano in the Okinawa Trough

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Magnetic minerals in the upper lithosphere generate magnetic fields when the minerals are in a cooler environment than their individual Curie temperatures. These magnetic fields have been utilized for studying crust and mantle dynamics such as most widely known example of seafloor spreading through the recognition of magnetization stripes on the ocean floor (e.g., *Vine and Matthews*, 1963). In addition, the application to detect volcanic edifices and hydrothermal alteration zones has been recently developed by using underwater vehicles, which enable to acquire near-seafloor magnetic anomaly (e.g., *Fujii et al.*, 2015; 2016). In 2014, we got a new discover of strongly magnetized basaltic volcanoes, known as the Irabu knolls, formed in the back-arc rift of the Okinawa Trough. Magnetic anomalies obtained by the ship and autonomous underwater vehicle around the Irabu knolls shows variation amplitude of 760 nT at sea-surface (summit water depth of 1630 m) and >10,000 nT at an average altitude of 100 m. Inverted magnetization intensity assuming 1-km magnetized layer shows ~18 A/m from sea-surface anomaly and ~60 A/m from near-seafloor anomaly. These values are considerably large compared with that of mid-ocean ridges (MORs), which are typically several A/m or less even on younger seafloors (*Dyment et al.*, 2015). These results imply that the Irabu knolls generate the strongest crustal magnetic field in the Earth. However, the cause of this extremely high magnetization intensity is still unknown.

In order to determine the source of these strong magnetic anomalies, we conducted rock magnetic and petrological studies of collected samples in the Irau knolls. Fourteen seafloor extrusive rocks including basalt, basaltic andesite, and andesite were obtained by the underwater vehicle *Hyper Dolphin* during YK00-06_leg2 NT11-20, and KY14-02 cruises. To characterize in rock magnetic properties and petrological signatures, we made a comprehensive data set of rock magnetic properties including natural remanent magnetization (NRM) intensity, magnetic susceptibility, grain density, coercivity, magnetic domain state (equivalent to magnetic grain size), Curie temperature (T_Q), Ti content (x) of titanomagnetite grain ($Fe_{3-x}Ti_xO_4$), titanomagnetite content (m), and mineral texture.

All samples contain titanomagnetite as main magnetic carrier and have not been affected by low-temperature oxidation (maghemitization). One sample shows the highest NRM value of 214 A/m. This sample shows single higher T_Q = 460˚C and lower x = 0.19 compared with MOR basalts, and indicates a magnetic domain state of complete single-domain (SD) with m = 0.8 wt.%. The other samples with complete SD also show relatively high NRM of 38–116 A/m and similar m = 0.7–1.1 wt.%. In contrast, samples with pseudo-single-domain (PSD) or multi-domain (MD) show small NRM intensities of 7–10 A/m but larger m = 2.5–3.2 wt.%. Low NRM intensity of 8 A/m was also observed for one sample with the contributions of superparamagnetic (SP) grains. This sample shows m = 0.2 wt.%, which is small compared with that in other samples with SD and MD grains, suggesting that crystal growth of titanomagnetite is insufficient due to the rapid cooling rate or reduction of pressure. These results demonstrate that the contribution of SD grains rather than abundant MD grains is clearly important for acquisition of strong NRM, and that rapid crystal growth inhibits the creation of titanomagnetite and enables the formation of SP rather than SD grains. Proper crystal growth rate forming a lot of SD grains is important for the acquisition of high NRM values. To conclude, we propose that the high magnetization of the Irabu knolls reflects accumulation of non-oxidized (fresh) low-Ti lava flows containing abundant

SD-titanomagnetite grains, formed under proper crystal growth rates.

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Keywords: Submarine volcanism, Back-arc rift, Magnetic anomaly, Rock magnetism, Okinawa Trough

Quantification of the effect of inhomogeneous magnetization or irregularity in shape on the measurement of remanent magnetization

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Quantitative assessments of the effect of inhomogeneous magnetization and/or irregularity in shape on the measurement of remanent magnetization were made experimentally and theoretically. Experiments were performed on artificial and natural samples, using a novel type of high-sensitivity spinner magnetometer. The spinner has a wide dynamic range from 10^{-10}–10^{-4} Am^2 and a resolution of 10^{-11} Am^2, incorporating two unique functions: a mechanism for adjusting flexibly the spacing between the sensor and the spinning axis, and a capability of measuring not only the fundamental component (5 Hz) but also the second (10 Hz) and the third (15 Hz) harmonic components. The former enabled the measurement of samples in any shape sized 10–50 mm, and the latter allowed the measurement of waveforms containing the harmonics leading to the analyses of their FFT spectrum. Numerical simulations using finite element method (FEM) were performed for assessing the effect of shape irregularity on the measured remanent magnetization. The effect of the heterogeneous magnetization was evaluated using a small dipole-simulating coil and a mini-core specimen of volcanic rock, and measured their magnetization by repositioning at different distances off the spinning axis. The effect of the offset was assessed in terms of the amplitude of the fundamental wave and the harmonics versus the amount of the offset. The measured amplitudes, without exception, increased with the amount of the offset, and their relationship was well approximated by a polynomial curve consisting of the second- to forth-order terms. This suggests that the contribution from the higher-order harmonic components could be represented in the form of a non-linear function of the offset distance. Measurements by a conventional spinner also demonstrated a similar increasing curve, but in association with a smaller increase rate and relatively large errors. The smaller increase rate is most likely due to its high-order low-pass filter and the large sensor distance for isolating only the fundamental wave component. However, the systematic increase with the offset, regardless of the type of spinner used, is contrary to the expectation that, given the same sample with the same magnetic moment, the magnetization measured for the offset and non-offset samples will be identical. This finding suggests that the intensity of magnetization measured with a spinner may include a systematic bias, particularly when samples contain a large amount of harmonic component that can be represented by an offset dipole. Theoretical analyses based on multipole expansion have revealed that the systematic relationship between the amplitude and the offset can be explained in terms of the dipole and higher-order multipole and their varying contributions dependent of the amount of offset. The FEM calculations were made for evaluating the effect of shape irregularity on the measured magnetization. The results were consistent with the experimental data from samples with the same properties as used in the model calculations.

Keywords: inhomogeneous magnetization, dipole moment , spinner magnetometer, multipole expansion, harmonic component

New measurement protocols for hysteresis reversal curves and identification of magnetic mineral components

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High-resolution first-order reversal curve (FORC) diagrams are being used increasingly in rock and environmental magnetism, including for detection of biomagnetic signals in sediments. Resolution can be a major barrier to obtaining high-quality FORC diagrams and time-consuming measurements that employ small field steps are necessary to resolve the finest features of a FORC distribution. We have developed a new experimental protocol with irregularly spaced field steps that allows different parts of a FORC diagram to be measured at different resolutions. Larger numbers of measurements can, therefore, be made in key regions of a FORC distribution to resolve diagnostic features at higher resolution. Specification of the field steps in the irregular grid is based on measurement of a major hysteresis loop; no *a priori* knowledge concerning the underlying FORC distribution is required. FORC diagrams obtained with conventional measurements and with our new measurement protocol give consistent results. We have also extended the applicability of FORC-type diagrams through use of a series of hysteresis measurements that provide information about remanent, induced, transient, and transient-free magnetization components. These measurements, and differences between measurement types, enable production of 6 FORC-like diagrams with only double the number of measurements needed for a conventional FORC measurement. These diagrams enable discrimination between magnetic signatures associated with each domain state. When analyzing samples with complex magnetic mineral mixtures, contrasting domain state signatures are mixed in a traditional FORC diagram, but these signatures can be identified individually with the 6 diagrams discussed here. The ability to make different FORC measurements and to identify separately each magnetic component in a conventional FORC diagram by investigating different magnetization types can provide much-improved understanding of the information provided by FORC diagrams. The diagnostic information provided by these additional FORC-type diagrams should assist substantially in magnetic unmixing of complex samples and in quantitative mineral magnetic interpretation.

Keywords: Geomagnetism, Paleomagnetism, Rockmagnetism

Revealing the role of microbial activity in the acquisition of NRM in aquatic sediments -- Insights from redeposition experiments

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Sedimentary rocks and sediments preserve continuous records for reconstructions of geological events. Magnetic records are among the most concerned sedimentary records across disciplines due to their application in synchronizing cores. In particular, the natural remanent magnetization (NRM) is of great interest as the derived relative paleointensity (RPI) reconstruction can provide high-resolution geochronological frameworks on a global scale. Despite the extensive application for decades, however, the underlying mechanisms of how paleomagnetic records are acquired and preserved in sediments are only partially understood. Moreover, with the biogenic magnetite, known as magnetofossils, being widely identified in sediments, questions about their effects on RPI reconstructions are posed given their unique properties with respect to the detrital magnetic components. With these questions in mind, we designed redeposition experiments to investigate how magnetofossils acquire remanent magnetization in fresh sediments. The dominant magnetic component of the sediments is single domain magnetite, presumably magnetofossils, accounting for ~87% of the magnetization in these sediments. The redeposition experiments were performed with such sediments in their original form whereby the living microorganisms (mainly non-magnetic bacteria) are preserved. We documented two major novel features of the acquisition behaviors in our experiments. First, the acquisition of these sediment particles after deposition is more effective than previously estimated. Second, the acquired remanent magnetization is unstable in a zero field. We discover that these features are associated with the microbial activities, and can be well explained by a bioturbation-driven acquisition model. It suggests that bioturbation plays an appreciable role in modulating the paleomagnetic records in sediments. This finding has a strong implication for improving RPI reconstructions in future.

Keywords: Natural remanent magnetization, sediment, bioturbation

Superparamagnetic magnetoferritin nanoparticles: syntheses, characterization and applications

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Ferritin is a widely existing iron-storage protein in many living organisms throughout animals, plants and bacteria. It is a cage-like protein with an external diameter of 12 nm and an inner diameter of 8 nm. The structure of mature mammalian ferritin consists of a 24-subunit protein, composed of heavy-subunits (H) and light-subunits (L). Within the ferritin protein cavity, there is a very weak magnetic hydrous ferric oxyhydroxide (ferrihydrite) mineral core. In the past few decades, great progresses have been made in synthesis of various strongly ferrimagnetic nanoparticles using ferritin proteins (e.g., Meldrum et al. 1992; Douglas et al. 1995; Kramer et al. 2004; Mann et al. 1993; Mann and Meldrum 1991; Yamashita et al. 2004). Importantly, through advancements in genetic engineering, the recombinant human H-chain ferritin (HFn) was developed and used to synthesize mono-dispersed, non-interacting ferrimagnetic magnetoferritin (M-HFn) nanoparticles. These biomimetic synthesized ferrimagnetic magnetoferritins have stoichiometric magnetite cores with nearly sphere in shape, extremely narrow size distribution, high crystallinity, and are superparamagnetic at ambient temperature (e.g., Uchida et al. 2006; Cao et al. 2010; Walls et al. 2013). Recently, we have well demonstrated that the M-HFn nanoparticles can be directly used to visualize diverse tumor tissues and in vivo imaging of microscopic tumors, due to their dual functionality of active tumor-targeting ability and inherited peroxidase-like activity (Fan et al. 2012; Cao et al. 2014; Cai et al. 2015). In this paper, we will present new results of syntheses, characterization, and biomedical applications of the M-HFn nanoparticles. It has been found that the magnetic properties, relaxivity and peroxidase-like activity of M-HFn nanoparitles are size dependent. Moreover, the cobalt-doped M-HFn nanoparticles (M-HFn-$Co_xFe_{3-x}O_4$) can enhance the peroxidase activity and tumor tissue visualization.

Keywords: Superparamagnetism, Magnetoferritins, Synthesis

A Magnetite-Based Biophysical Hypothesis for the Radiowave Detector in Migrating and Homing Animals: Magnetoacoustic Transduction

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Two major biophysical theories have been proposed to explain how migrating and homing animals could make use of the geomagnetic field, including the presence of specialized receptor cells containing crystals of biologically-precipitated magnetite (*1*), or quantum-mechanical effects on electron spins in the photo-active pigment, cryptochrome (*2*). Evidence exists for both theories: Nearly 20 studies have shown that many animals change their behavior when subjected to a short magnetic impulse that exceeds the coercivity of biologically precipitated magnetite crystals, and proponents of the quantum compass idea argue that the disruption of magnetic behavior by radio frequency (Rf) waves in the mid-wave band (.1-5 MHz) can be explained by interference with the hyperfine transitions between singlet and triplet quantum states.

Two separate and unrelated studies now lead us to propose that biological magnetite might also be able to account for the radio wave effects, without the need for a cryptochrome sensor. First, Kellnberger et al. (*3*) demonstrated that energy absorbed in single-domain magnetite nanocrystals by the oscillating magnetic field vector in an incipient radio wave is converted to ultrasound at the second harmonic of the driving frequency (e.g., a 0.5 MHz signal produces ultrasound at 1 MHz); this ‘magnetoacoustic’ effect works, and they were able to measure ultrasound at double the Rf frequency in aqueous solutions containing SD nanophase magnetite when exposed to weak Rf radiation. Second and quite independently, Kubanek et al. (*4*) discovered a class of trans-membrane ion channels that were activated by ultrasound in this same frequency band. If those ion channels were expressed in the lipid-bilayer membranes surrounding magnetosomes, they could constitute the biological radio-wave receptor (*5*). Using scanning SQUID microscopy of bovine muscle tissue (‘wagu beef’), we have recently shown the common presence of common ferromagnetic clusters at ppb to ppm levels, with rock magnetic properties consistent with biological magnetite; some of these, if present in sensory cells, might be the radio wave detectors.

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Keywords: Single-Domain biogenic magnetite, Magnetoacoustic effect, magnetic field sensitivity in animals

